# Tectonic Studies on Wooden Arched Bridge. As the Case of Span in Chinese Wooden Construction Tradition

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ABSTRACT: Strong tradition of Chinese wooden structure has been noticed by architectural academia for decades, while many existing interpretations were based upon stylistic architecture theory, so that the scientific and tectonic issue of this tradition has not be expressed well. This situation very much influenced Chinese architects to learn the wooden structure as the cultural tradition and transformed into the application of modern architecture in China. In order to change this situation, we turn to the tectonic approach. Structure issue of how to make the span Chinese wooden construction tradition became focus of our wooden tectonic studies. As the case of span in Chinese wooden construction tradition, this study is focused on the wooden arched bridge, be described as "Rainbow Bridge" in some case, a special ancient construction in wood and has been used widely historically, can still be fund in the region of the Southern Zhejiang and Northern Fujian Provinces. Authors made decent inventory for this important culture heritage of Chinese wooden construction on the site, after the collection of information from the site, a historical / environmental and typological study has been made, in order to explore the relation between the wooden structure form and local cultural / environmental definition. Furthermore, authors made the profound studies on structure, material, and construction process of the structure forms with the built wooden models, which express the technique element of the wooden arched bridge in the analytical way. Based upon the scientific analysis, authors have been able to explore the construction process of the bridge, and also the evolution of typological development to answer the made of this special bridge type. With those studies, authors tried to re-evaluate the meaning of tectonic culture and mountainous human habitat culture on the wooden construction.

## BACKGROUND: WOODEN STRUCTURED ARCHITECTURE IN CHINESE CIVILIZATION INFORMATION

Looking at human construction in a sustainable world, there are two kinds of materials have been mentioned more and more in our day: they are soil and wood, perhaps because they are both recyclable by nature and thus ecological.

### Wooden Architecture Became the Main Development in Chinese Tectonic Culture

Soil and wood are both the most commonly used structural materials in traditional Chinese civilization. As the Chinese architectural historian Liang Sicheng said:

> It is demonstrated that soil and wood have been main materials, which Chinese architecture adopted for its whole history, based upon the phrase 'the work of earth and wood' which generally applied to all construction engineering in Chinese tradition. (Liang 1984, p.340)

Historically, "*the work of soil and wood*" became almost the Chinese description of construction and engineering. However, in modern Chinese, it has been especially applied to the subject of civil engineering. Based upon these two natural materials, clearly two trends of construction and habitation in Chinese civilization developed: cave and nest. In the most ancient documents, they had been described:

> Formerly the ancient kings had no halls or houses. In winter they lived in caves which they had excavated, while in summer they lived in nests which they had framed. (Needham 1971, p.120)

In this sentence, the two origins were described from the earliest times in relationship to the seasons. The logic is clear: utilizing the cave underground against a cold and dry winter, and utilizing the nest over the trees against a hot and humid summer. These two origins of architectural types had been utilized for different seasons in China, according to climate. Another sentence from historical documents would also be meaningful for these two origins in ancient Chinese habitations: "Lower region, resident in nests; while upper region, resi-

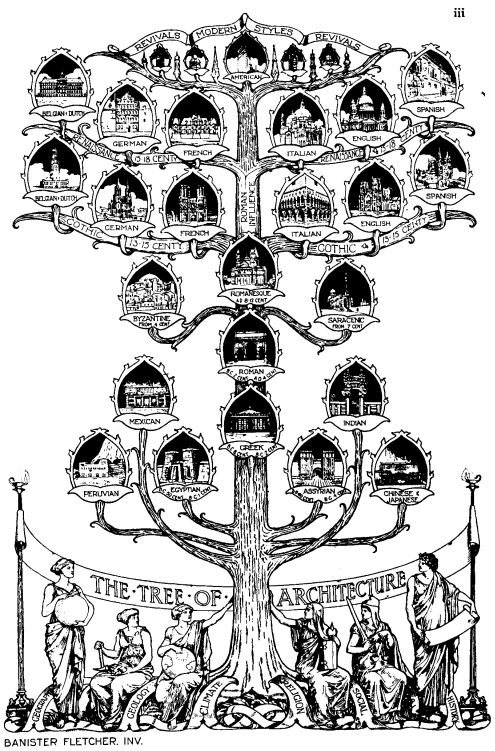
dent in caves" (Meng Zhi - Teng Wen Gong, 300 B.C.). "Lower region" means southern China and "upper region" means northern China. So, the logic of the description is similar to the sentence above referring to the seasons: the winter "cold and dry" is coupled to the north of China, and "hot and humid" to the south of China. In the ancient Chinese cosmological concept caves and nests became fundamental habitations, integrated with time and space. Even today we see these two original habitations in Chinese vernacular architecture. The famous "yao dong" is still being used in the wide region of the yellow earth (loess) plateaus, while variations of the "nest" in southern China are to be found in a general type of "gan lai", which is a skeleton or framed structured with wood or bamboo, lifted above the floor at a certain distance from the ground. Archaeological research supplied the evidence that ancient Chinese habitations developed from underground caves and nests lifted above the ground, passing through shelters made of a mixture of timber and earth on the ground, to structured wooden buildings. Wooden structured architecture became the chief system used in Chinese architecture throughout most areas of China, no matter whether north or south.
There is already enough evidence of the great quantity and rich usage of wood all over the vast country and throughout the historical development. Through cultural influence and international exchange, wooden architecture became the major architectural system not only in China, but also throughout the whole of Eastern and Southeastern Asia and specifically in Japan and Korea. The main type of Chinese wooden architecture is the wood-framed structural system.

**Existing Architectural Interpretations from the Standpoint of "Style"**

Ever since the end of the 19th and the beginning of the 20th century, Chinese wooden architecture has been continuously interpreted, first by Western, and then later on by Chinese architectural historians. Based upon the then current architectural concept of "classicism" however, those interpretations were severely limited.

*Representative Western Interpretations from the Colonial Period*

The typical form of interpretation by Western architectural historians in the colonial period is represented by James Fergusson (1808-1886) and Banister Fletcher (1866-1953). Both were eminent British architectural theorists who dominated the Western view of architecture for a long time, especially in the English-speaking sphere of influence, and they also made their influence felt in Asia, including in India and the Far East through British colonialism.
James Fergusson was the first to describe Chinese architecture as part of Eastern architecture in his "History of Architecture". Yet at the same time he was uncertain about Chinese architecture since very little information was available to him at the time. His expression of surprise about the absence of monuments in Chinese architecture, especially in comparison to the Egyptian, was typical of a European with a classical view of architecture at the end of the 19th century. (Fergusson 1865, p.736)



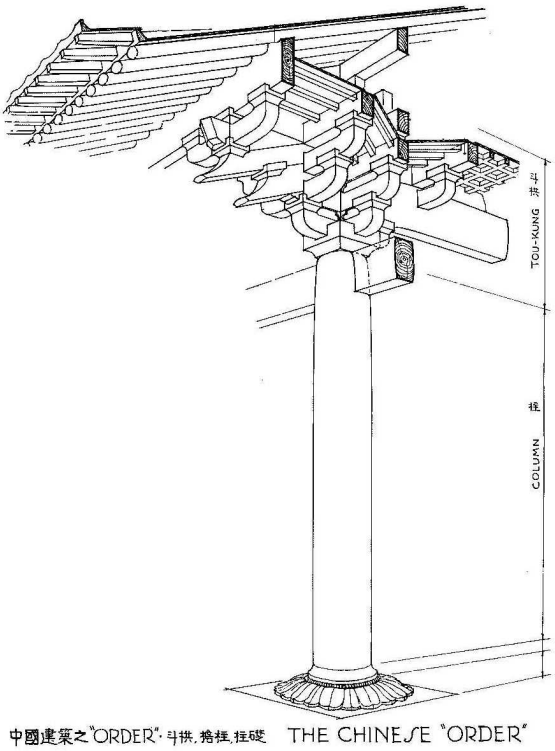




Figure 1(left): The Tree of Architecture; (Fletcher 1896, p. 8)
Figure 2 (right): Liang Sicheng's Stylistic Interpretation of Chinese Wooden Architecture, "The Chinese Order"; (Liang 1989, p. 15)

The predominant view, Sir Banister Fletcher's "A History of Architecture", edited and revised more than twenty times until 1996, exerted a strong influence on architectural research and education. The changing versions of his book clearly show how the Western view of architecture changed from the end of 19th century to the present (see Fletcher 1896). His descriptions and explanations of Chinese architecture added to the fourth version in 1901 were categorized as non-European architecture under the general title of "The Non-Historical Styles". Combined with the famous "Tree of Architecture" (Figure 1), which Fletcher used as a fundamental description of the worldwide historical evolution of architecture, Chinese architecture occupies the same position as Japanese, Arabic, etc. They are all put into the branches. Obviously the main evolution of European architecture was expressed in the trunk. Fletcher represented a view of architecture based upon classicism. With this interpretation of "The Non-Historical Styles" and "Tree of Architecture", Fletcher became also a typical representative of colonialist thinking among architectural historians. It is not difficult to see Fletcher's classicism and colonialism reflected in his written comment to "The Non-Historical Styles" (Fletcher 1901). It certainly made architects and scholars in non-European countries unhappy.

*Representative Interpretations from the First Generation of Chinese Architectural Historians and Influence Continued*

Following the interpretations of Chinese wooden architecture by Westerners, Chinese scholars with strong nationalistic interests, reacting to western colonialism, developed their interpretations based upon the principle of "restoring the national treasure" in the 1920's and mainly in the 1930's. These were mostly young architects educated abroad who returned to become the first generation of Chinese architects and architectural historians. Liang Sicheng was the chief representative of this generation. His goal was to interpret Chinese wooden architecture in order to establish an independent Chinese architectural academia and to counteract the Western colonialist interpretation. However, what the academic basis these scholars began with was, unfortunately, the classical tradition of the Paris Ecole des Beaux-Arts. Thus their interpretations of Chinese wooden architecture remained most definitely both classical and style-bound.
They interpreted Chinese wooden architecture based on this classicistic viewpoint. As in a classical building in the West, the elevation of a Chinese temple would be defined as three parts with a "platform or stylobate", a "middle", and a "roof" (similar to a classical analysis of Renaissance architecture). Proportions of the elevation were emphasized as an indication of the "styles", especially used to distinguish the different dynasties. The most famous of Liang Sicheng's definitions concerning Chinese architecture is probably "The Chinese Order" (Figure 2). It is founded upon the combination of three parts: base, column, and "dou gong" (cantilever brackets). Especially the "dou gong" was emphasized because of its significance in comparison to the column capital of the West. Furthermore, he declared the Song-Dynasty "cai" (written ts'ai in the Wade-Giles latinization system) or the Qing-Dynasty "dou gong" as the modular unit for the composition of Chinese classical architecture. Of course his focus lay on the idea of "façade". In Liang Sicheng's "History of Chinese Architecture" (Sicheng 1989), historical development of Chinese architecture was interpreted as the evolution of dynastic styles, and these dynastic styles based upon the expression of "façade", which reflected the manner in which the idea of "style" was applied in classical Western architectural history. We can clearly understand how Liang constructed this kind of academic base when we know his educational background: from 1924 to 1928 he studied at the University of Pennsylvania under Paul Philippe Cret (1876-1945), who then dominated American architectural academia and was also an important architect representing the tradition of the French Ecole des Beaux-Arts (Fairbank 1994, p.26).
These interpretations then became the main body of Chinese architectural history. Even today, most Chinese architects learn this system as part of their professional education. There have been continued interpretations both theoretical and practical in Chinese architectural academia over the decades and they have influenced the development of Chinese architectural education until the present, however they have moved away from the basic idea of wooden structure. This trend has also confused the concept of modern architecture with a postulated "Chinese National Style".

## THE WOODEN ARCHED BRIDGE: SPAN AS STRUCTURE

Therefore the architectural classicistic or stylistic view was adopted not only by western historians like James Fergusson and Banister Fletcher but also by Chinese architectural historians like Liang Sicheng. This view developed totally divorced from the context of Chinese wooden architecture, and if we search at a deeper level, it actually bases on the "noble" European construction context, typically on the evolution of stone architecture in direct lineage from Egypt to Rome then to the Renaissance, etc. Thus the problem automatically arose when historians tried to interpret Chinese wooden architecture based on such a foreign stylistic background.

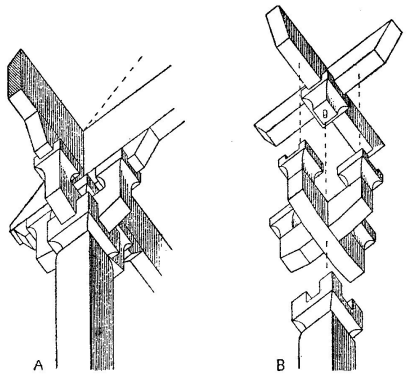
### Reinterpretation of Chinese wooden Architecture based on a tectonic View

Gradually more and more architects noticed that if a defined Chinese architectural culture developed not along stylistic guidelines, it could still be based on a tectonic evolution. Chinese wooden architecture lends itself very well to a tectonic interpretation in a relatively direct manner.
Our revised academic view derives firstly from a lesson about how to interpret non-European architecture fairly, for example by looking at the French architectural historian Auguste Choisy (1841-1909), a contemporary of Banister Fletcher. With his engineering bias and through his teaching at the Ecole Polytechnique and Ecole des

Ponts et Chaussées, both schools with vastly different approaches from that of the Ecole des Beaux-Arts, Choisy developed the tectonic theory of Eugène Emmanuel Viollet-le-Duc (1814-1879). His "Histore de l'Architecture"(Choisy 1899) was published just three years later than Fletcher's, but it delivered quite different information to readers about Chinese as well as Eastern Asian architecture. As Kenneth Frampton wrote:

> For Choisy the essence of architecture is construction, and all stylistic transformations are merely the logical consequence of technical development: 'To parade your art nouveau is to ignore the whole teaching of history. Not so did the great styles of the past come into being. It was in the suggestion of construction that the architect of the great artistic ages found his truest inspiration.' (Frampton 1985, p.19)

With this approach, Choisy's view of Chinese and Japanese architecture was tectonic. In chapter VI "Chine, Japon", as in other chapters, he presents analytical drawings of Chinese and Japanese architecture that deal with issues ranging from spatial organization to detailed wood construction. It is a very interesting piece of work with an attempt to explain the logic of design and construction. We cannot discern any inappropriate critical issues about Chinese and Japanese architecture in this chapter. Compared with Fletcher's contemporaneous interpretations, it makes more sense than any discussion of style, even though Choisy's approach itself was still quite primitive (Figure 3). As a result, the comparison between Choisy and Fletcher taught us how to interpret non-European architecture fairly and meaningfully.
Another lesson to be gained is to review the famous debate about why Chinese architecture is made of wood, a question that was originally posed by western scholars like James Fergusson who believed that architecture must be monumental and permanent as a sort of "grand art" as it was in ancient Europe. This question has puzzled several generations of Chinese architectural theorists and historians, many research projects have appeared on this theme from many different standpoints. The meaning of the original question automatically disappears as soon as we turn our attention to the interpretation of Chinese wooden architecture as a tectonic issue. Since it is clear that to utilize wood for construction is not an exclusively Chinese historical privilege, the question actually should concern what we consider to be architecture. In the western classical tradition, architecture is narrowly defined only as the noble and monumental, mostly made of stone, so that the written history concentrates almost exclusively on stone. All other buildings made of lighter and less permanent materials, such as wood, are not recognized or evaluated as architecture. This view of architecture academically supported Euro-centrism and the western colonial approach. Based upon these considerations, it becomes necessary to accept the tectonic in order to interpret Chinese wooden architecture, if Chinese architectural theory and history wish to depart from narrow-minded western classicism academically and Euro-centrism politically.



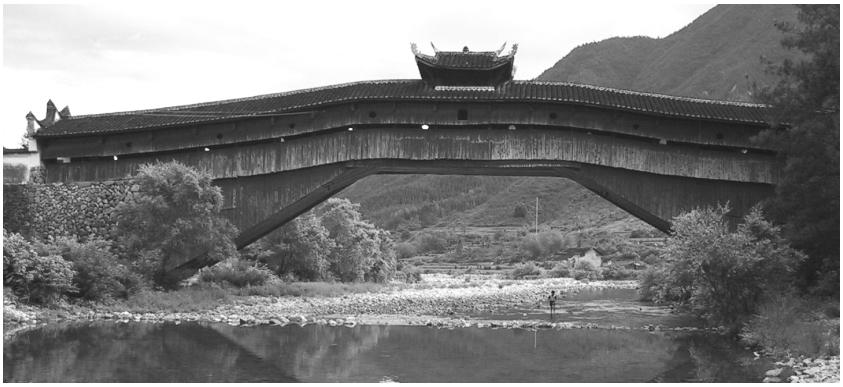



Figure 3 (left): About Chinese wooden construction; (Choisy 1899, p. 75)
Figure 4 (right): Wooden arch bridge; (Photo by the author)

**RESEARCH ON A WOODEN ARCH BRIDGE**

For most architects to adopt the tectonic view in architecture would mean:

> A certain expressivity arising from the statical resistance of constructional form in such a way that the resultant expression could not be accounted for in terms of structure and construction alone. (Sekler 1995, p.19)

The technical process of construction must then be essential. It follows first the definition of the material, then the definition of a certain way of construction, and finally the attainment of the structural form. Over the past few years we have combined this methodological definition of wooden tectonic study with a defined teaching process for graduate students at Nanjing University's School of Architecture. Following the steps of "material", "construction", and "structure", the analysis of traditional wooden architecture focuses finally on the final step "structure" in the basic formation of types.
There have been a multitude of interesting traditional types of wooden architecture in China. Many research projects have focused on these different types based on their functional classification. Our selection differed in that it was based upon tectonic considerations, so that the criteria for our selection are more related to a clear technical definition rather than architectural expression. Nevertheless, we believe that by applying the

tectonic view to architectural studies we do not reduce the expressivity of a wooden structure. That remains intact and represents its architectural quality.
Once the material and construction method have been defined as Chinese wooden architecture, the structural form then becomes the issue of our selected object. So we defined span and height as the core parameters of our paradigm. For the span, we chose an ancient arched bridge in wood that was used widely historically and that can still be found in southeastern China. For the height, we chose the wooden drum tower of the Dong Minority population in the southwest of China. The Dong still retain their vibrant, traditional tectonic culture. In both these cases, we conducted our research on two basic questions: the one was to explain the process of construction, that is to answer how it was built, and the other was to interpret the typological development compared with other wooden structures, that is to answer how the unique form of structure came to be. Aside from these two questions however, we also conducted the necessary investigation and analysis into aspects of the relevant environmental and social backgrounds. Here I will only present the wooden arched bridge as a case study of span as the structural parameter.

*The wooden arch Bridge in southeastern China*

This unique type of wooden arch bridge results in a very unusual form, which has intrigued many bridge engineers and architects and fascinated tourists (Figure 4). However, the type originated in an ancient form, the arched "Rainbow Bridge", a significant historical structure built in the Song-Dynasty capital (AD 960-1127). It was a beautiful type of wooden bridge that quickly proliferated widely and that still can be seen in Japan today, but in China its only remaining trace is as the central focus of the famous ancient painting "Along the River During the Qing-ming Festival" by Zhang Zheduan (Figure 5). His well-known historical bridge inspired many research projects, so that when an analogous wooden arched bridge type was found in the south of Zhejiang and the north of Fujian Provinces, most scholars immediately recognized it as a relic of the Song "Rainbow Bridge". In reality however, the wooden arched bridge type located in southeastern China is not the same as the "Rainbow Bridge" in its construction. They do however share a similar structural concept.
An inventory we made in this mountainous region in 2001 enabled us to locate more than twenty examples of this type, some of which are still in use. Still more fortunate, we found a few local carpenters who still master their construction technique. Based upon the important insights and ample material we collected from our site investigation, we were afterwards able to model construction studies both in wooden models and virtually on the computer. We subsequently returned to the site to meet with the local bridge carpenter, asked him to examine and correct our model with regard to assembly and disassembly in order to ensure that we really understood the whole traditional construction process correctly.

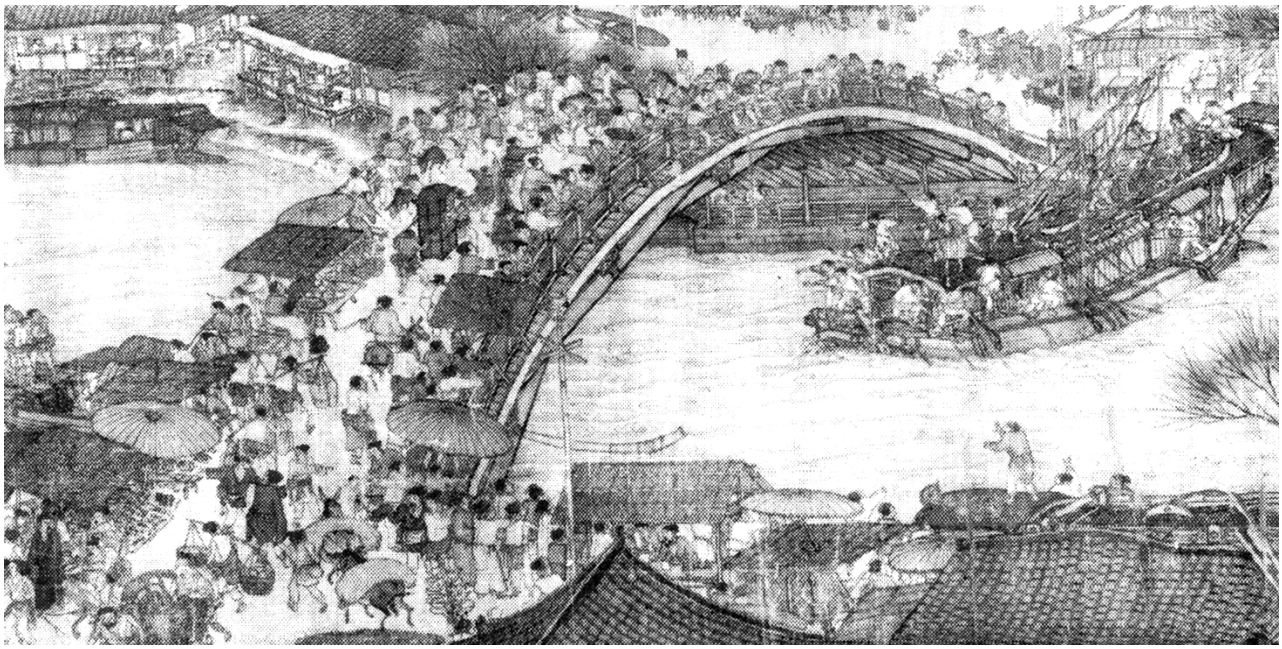


Figure 5: "Rainbow Bridge" from "Along the River During the Qing-ming Festival";
(Song Dynasty's painting by Zhang Zheduan)

*Analysis of the timber construction*

The bridge presented an intriguing form with its complicated organization and sophisticated construction. The only way we could understand it was by making the model and analyzing its construction. Based upon the models we made, we divided the construction process into four parts or steps (Figure 6):
The base: The foundation was made of masonry, and in most cases the builders chose the natural rock for the bridge to stand on. This was the only masonry work in the whole construction. Nevertheless it was still built under

the control of the chief carpenter who was in charge of the entire project. The quality of construction of this part is obviously very important, just as it is for any other bridge foundation.
The primary system with three rows of timbers: This first system forms a structure with rows of wooden timbers made of fir. Each row normally consists of nine timbers, beginning with two base timbers that are fastened with tenons to two thick timber beams made of some other hardwood. This system takes the shape of a giant figure eight in Chinese letters, and forms the basic framework to support the whole system.
The secondary system with five rows of timbers: Adding to the first system, this system is made of five rows of timbers. Each row has the same number of timbers as the first system, but shifted to fit each other so that their connections are shifted by half a timber length. These are fastened to four other timbers. They are organized with the same logic as the primary system, but the whole is entwined with the first system so that the two together form an arch.
The horizontal purlin system: The longest timbers connect the top of the arch with the two sides of the masonry base. These are added on to the arch and combine with the other two systems so that the whole bridge becomes a double-layered structural system. This braces it against horizontal forces. It also helps to support the horizontal bridge deck.
The floor and cover system: The wooden floor lies over the top of the structure, and a wooden-framed building built above this covers and protects the whole structure. The whole becomes a covered corridor for the deck and the wooden arched structure beneath is totally covered and protected from the weather.

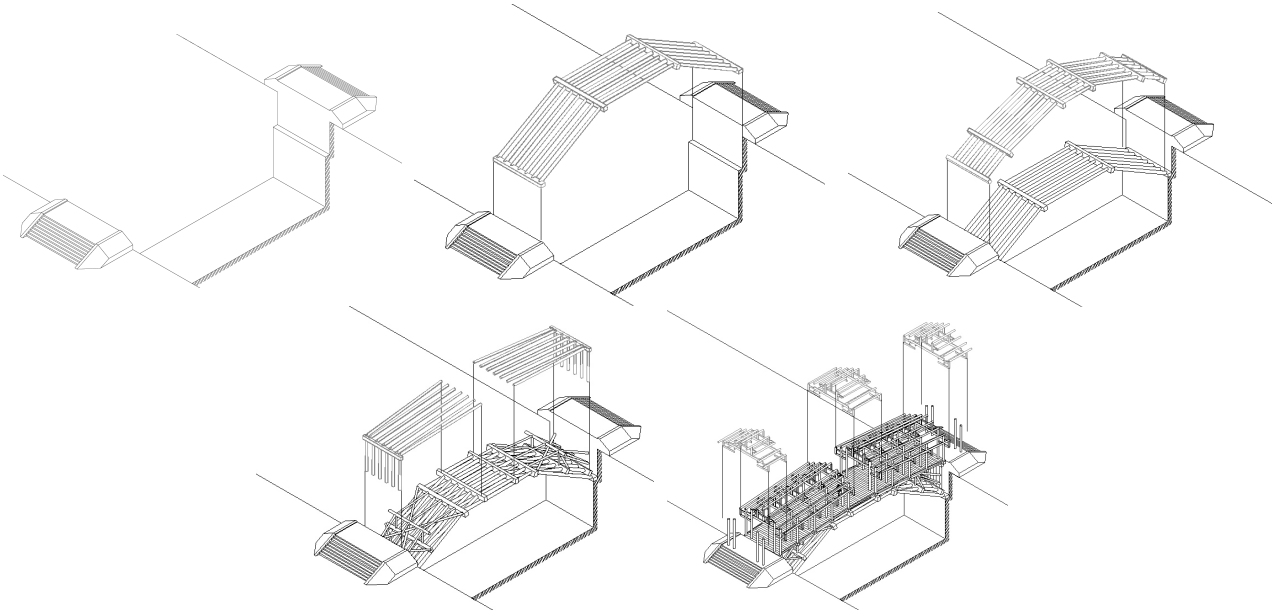


Figure 6: The construction process of the wooden arched bridge; (Author's drawing)

*Analysis of the typological development*

Such a sophisticated and unusual traditional structure is often thought to be the brilliant creation of a single historical person, and many studies of such objects are based on just such an understanding. While we do not believe such a sophisticated and complex structure to be directly created by any person in history, we find it more probable that traditional and regional wooden tectonic features obey established rules of vernacular construction to develop step by step following a process of natural evolution in an additive development. It is highly unlikely that any one person can be called the creator or inventor. It is therefore much more meaningful to apply a typological study to analyze the development, rather than to try to discover a first builder or designer (if such are to be found at all). Our analysis presumes to explain the wooden arched bridge as a sophisticated type that might have developed from other primitive types so that it is probable that they should all be related one another.
Our analysis began from the simple wooden beam bridge as the postulated most primitive type with a log laid horizontally over an opening. The development then proceeds with the question how a bigger span could be made using additional timber elements. All in all we defined six types, and we found all of them in actual examples (see Appendix):
Type 1: Flat beam bridge: the most primitive bridge in mountainous areas;
Type 2: Folded floor with frames: from the Song-Dynasty painting;
Type 3: Double frames from the banks: from the Song-Dynasty painting;
Type 4: Figure-eight-shaped frames (see Ref. "Chinese a"): Shengxian Bridge in Shouning County, Fujian Province;
Type 5: Combination frames: Meishuban Bridge at Xinchang, Zhejiang Province;
Type 6: Wooden arch: Lanxi Bridge at Qingyuan, Zhejiang Province.

These six types in the evolutionary diagram explain the developmental process of the specific form of the wooden arch bridge and render the complex structure comprehensible. However, in order to demonstrate further the logic of typological development, we hoped to find yet other types beyond the six we had originally defined. This happened three years later, in 2007 with the help of local people in the area and especially the bridge carpenter in Pingnan County, Fujian Province. We discovered an additional "Double-eight-shaped frame" (Figure 7) that we were able to plug in perfectly between type 5 and type 6. Since then we have learned that "Eight-shaped frames", "Double-eight-shaped frames" and "Wooden arches", were all pragmatically selected in construction according to the exact specifications of each project. Somehow the series of typological development proved to be more important than any one specific type.

Figure 7: The newly discovered additional type of "Double-eight-shaped frame"; (Research model by authors)

*Analytical comparison of the typological development of wooden arch bridges between China and Switzerland*

Based upon the analysis of the typological development of wooden arch bridges in southern China, we turned our view to Europe, especially Switzerland, where there are many interesting traditional wooden bridges. There was certainly a similar typological development for those bridges from simple and basic types to the complicated and sophisticated. We thought it might be rewarding to initiate a comparative study of both the Chinese and the Swiss series. We took the systems or "Tragwerksysteme" from "Holzbrücken der Schweiz – ein Inventar" by Werner Stadelmann (Stadelmann 1990), which illustrated several series of developments with "Hängewerke", "Sprengwerke", and "Hänge-Sprengwerke". It is clear that most of the Swiss covered wooden bridges were developed on the basis of the system "Hänge-Sprengwerke", in which the girder frame forms the basic structure, even though the supporting frames developed from "einfache" to "doppelte" to "Bogentrag-" and "kombinierte Tragsysteme". (Appendix 2)
When we compared these to the Chinese wooden construction tradition, we noted that the typological development displayed some similarities to the European, especially the "double frames" in China corresponded to "doppelte Systeme" or "Sprengwerke" in the Swiss systems. However, there are differences too, for instance that the Chinese have nothing that corresponds to the European "Hängewerk" with the "frames" passing above the bridge deck. The entire development of Chinese supporting systems is limited to systems under the deck. Even the arch type, being the most complex form of this development is also totally under the bridge surface. This may be the chief reason for the limitation of traditional Chinese technical capability to maximum spans of 35 to 38 meters, whereas the Swiss wooden bridges, combined with arch, girder, or frame could easily span 40 to 50 meters.

## CONCLUSION: CORRIDOR AND ARCH

Comparing Chinese and Swiss wooden bridge construction gave us an interesting understanding of the possibilities of the tectonic study. We recognized as a feature of Chinese traditional wooden architecture as demonstrated in those bridges, the separation between a structural part with an arch and an "expressional part" with a superimposed corridor. The Swiss examples integrate the two parts. The definition of the Chinese bridges has long confused us. In Chinese they are traditionally known as "corridor bridges" (lang qiao). We have long refused this terminology, as we believed that their major characteristic should be the structural wooden arch. However, most of them are covered by the linear, separate corridor structure on the top. Although this may be considered a missed opportunity structurally, there are other advantages on an architectural level if we shift our focus to the Chinese bridges as an expression of an overall integration of corridor plus arch.
It seems that Chinese wooden construction tradition kept a clear separation between supporting system beneath, the bridge surface above, and the roof of the corridor that covered all. Whatever structure the supporting system developed, it was limited under the deck and could never be touched by the people passing through the corridor on the bridge. That made the corridor part, which is always constructed as a functional

public building rather than a mere passageway, with a romantic roof and strong rhythm of columns, certainly more impressive. The reality is that the elegant arched structure with its attractive roofed corridor was understood to be integrated with the scenic background of mountain and water, as a public place and "a piece of architecture".

Furthermore, as an important and prominent local building, the bridge always played a crucial role as the entrance to a settlement. The traditional idea of geomancy or "fengshui" invariably played an important role in the planning of mountainous villages to guarantee them a good location related to the natural environment. The bridge had to provide an attractive public space for locals and visitors. As the very traditional concept of gathering place, it always served also as a temple inside the corridor. So, the corridor of the bridge became a very human temple, to be convenient both for people to pray and for God to be prayed to. It perfectly demonstrates Martin Heidegger's idea of a bridge as "the simple onefold of earth and sky, of divinities and mortals, to enter into a site by arranging the site into spaces" (Heidegger 1971).

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Fergusson, J., 1865: *History of Architecture in All Countries, from the earliest times to the present day*. Vol. II, Part III, Bk. VII, Ch. I. London: "*Notwithstanding all this, it certainly is curious to find the oldest civilized people now existing on the face of the globe almost wholly without monuments to record the past, or any desire to convey to posterity a worthy idea of their present greatness. It is no less remarkable to find the most populous of nations, a nation in which millions are always seeking employment, never thinking of any of those higher modes of expression which would serve as a means of multiplying occupation, and which elevate while feeding the masses; and still more startling to find wealth, such as the Chinese possess, never invested in self-glorification, by individuals erecting for themselves monuments which shall astonish their contemporaries, and hand down their names to posterity*."

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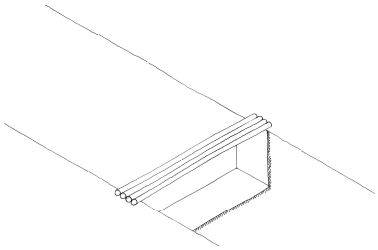
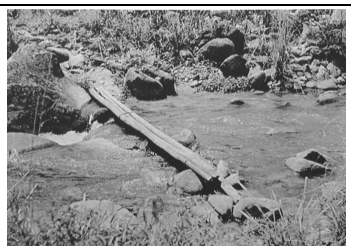
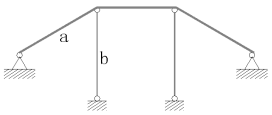
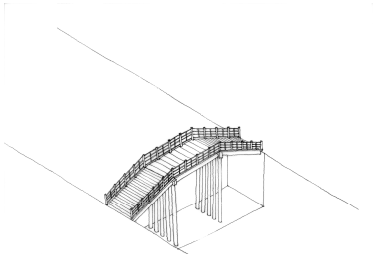
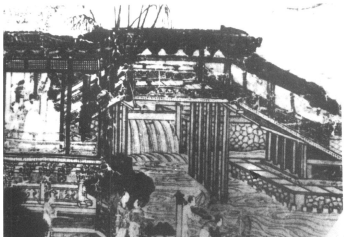
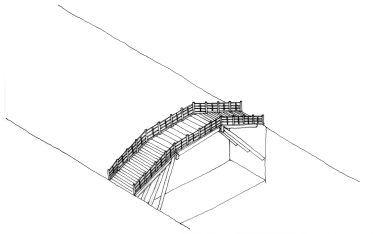
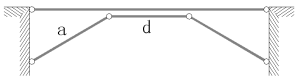
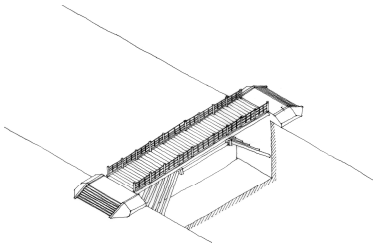
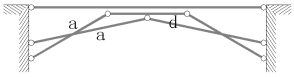
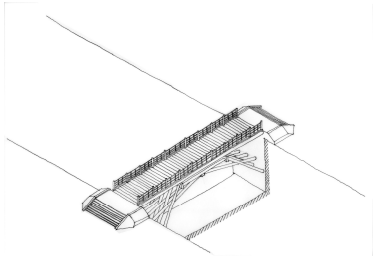
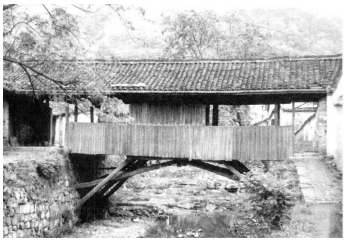
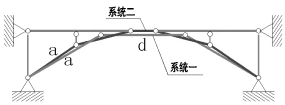
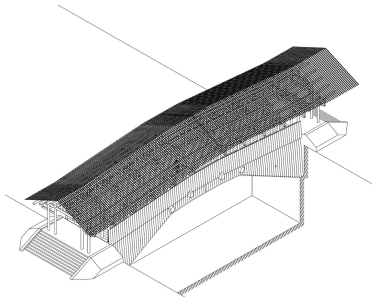
**APPENDIX: Analysis on typological development of wooden arched bridge**

| Type | Symbol of Structure | Typology | Cases |
|---|---|---|---|
| Type 1, Flat Beam Bridge |  |  |  The most primitive bridge |
| Type 2, Fold Floor with Posts |  |  |  From Song Dynasty's painting |
| Type 3, Double Posts from Banks |  |  |  From Song Dynasty's painting |
| Type 4, Eight Shape Posts |  |  |  Shengxian Bridge at Shouning County, Fujian Province |
| Type 5, Combination Posts |  |  |  Meishuban Bridge at Xinchang, Zhejiang Province |
| Type 6, Wooden Arched |  |  |  Lanxi Bridge at Qingyuan, Zhejiang Province |